D1 - 00

SPECIAL REPORT FOR SC D1
(Materials and Emerging Test Techniques)

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Special Reporters

1. General

The aim of Study Committee D1 is to facilitate and promote the progress of engineering and the international exchange of information and knowledge in the field of materials and emerging test techniques. The committee contributes to this information and knowledge by synthesizing state-of-the-art practices and by developing recommendations.

These activities include follow up and evaluation of new developments within:

- new and existing materials for electrotechnology,
- diagnostic techniques and related knowledge rules,
- emerging test techniques which may be expected to have a significant impact on power systems in the medium to long term.

2. Group Discussion Meeting

SC D1 invited for the Group Discussion Meeting contributions within three preferential subjects (PS), as follows:

Preferential Subject No 1: Electrical Insulation Systems under DC Voltage
- Material properties.
- Space and surface charges & potential distribution.
- Long term performance.

Preferential Subject No 2: Emerging Test Techniques and Diagnostic Tools
- UHVAC and UHVDC.
- Atmospheric and altitude corrections, harsh conditions.
- Development of new diagnostic and analyzing methods for asset management.

Preferential Subject No 3: Properties and Potential Applications of New Materials
- Materials for field grading.
- Eco-friendly materials.
- Superconducting materials.

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In total, 30 papers have been accepted of which 4 papers cover Preferential Subject No 1, 17 papers cover Preferential Subject No 2, and 9 papers cover Preferential Subject No 3. In the following parts of this report each of the preferential subjects is discussed separately, with a division to some specific for the submissions groups.

3. Preferential Subject No 1 – Electrical Insulation Systems under DC Voltage

3.1 Overview of submitted papers

The submitted papers cover a range of material aspects related to applications in HVDC systems and include insulators for hybrid AC/DC overhead lines, materials for compact HVDC gas insulated systems as well as materials for HVDC cable insulation.

Paper D1-101 discusses design criteria for outdoor composite insulators operating under combined electric stress in hybrid AC/DC overhead lines (OHL). This work has been driven by a need to convert some of the existing 380 kV AC circuits into DC circuits for increasing energy transfer capacity in German power grid. Today, the recommended procedure for selection of hybrid line insulators is mainly based on field experiences gained either from AC or from DC applications. One proposes taking into account the ratio between DC and AC components in the overlay electric stress. For DC component >10% the design should follow the approach as for DC application, where the pollution severity dominates as the dimensioning parameter. For improving the selection process, a range of research activities have been undertaken. Simulations of the electric stress to which insulators are exposed in a hybrid AC/DC line are presented, which have provided a base for development of adequate design tests and accelerated material aging tests.

Papers D1-102 and D1-103 report on investigations related to insulation performance in compact HVDC gas insulated systems. The first paper (D1-102) presents simulations and measurements of potential and charge distribution along spacers of various geometrical configurations. By varying the levels of bulk and surface conductivities of the spacer materials as well as by taking into account their dependence on temperature, conditions for reaching stationary resistive field distributions are explained, which in turn opens a way to its control. Benefits provided by use of spacer materials having field grading properties are also demonstrated, which may allow for additional size reduction of gas insulated systems. In addition, a possibility to introduce air-like gas mixtures into HVDC gas insulated systems is discussed with the aim to potentially replace N_2/SF_6 mixtures. The second paper (D1-103) also discusses the factors influencing electric field distribution along and inside solid parts of HVDC GIS. An electro-thermal numerical model is presented that allows for predicting the field distribution under steady-state and transient conditions. It takes into account the experimentally verified various properties of the solid and the gaseous media as well as the phenomena taking place at interfaces.

Paper D1-104 presents considerations on the requirements that need to be set on properties of insulating materials for securing a good performance in HVDC cables operating at voltage levels well above 320 kV. This task calls for a further improvement of material's electrical properties as well as a good control of its thermal and mechanical behaviour. It is demonstrated that the required low DC conductivity and high breakdown strength can be achieved through increasing physical and chemical cleanliness, i.e. by reducing the content of potential charge carriers and free polar groups available for the conduction process. Here, the type of vulcanization process and removal of its by-products also play an important role. This approach has been used for developing a new material for DC applications and a comparison of its properties with those of a standard XLPE material is provided.

3.2 Questions for Preferential Subject No 1

Question 1.1 What is the technical justification for adopting the 10% DC/AC field ration as the design rule for insulators operating in hybrid overhead lines? Are there any other concepts competing with this idea?

Question 1.2 What will be the optimal design and electric conductivity of epoxy insulators in gas-insulated HVDC GIS/GIL with respect to resistive field distribution, temperature gradient and operational voltage stresses? Are the simulation results verified by experiments on real size equipment? What test procedures are considered suitable to verify the long-term performance of gas/solid insulation systems for HVDC GIS/GIL?

Question 1.3 Stabilizing additives are usually added to polyethylene for improving its long term protection, so the material will degrade neither during cable manufacturing process nor during its service. Is there any concern or challenge when stabilizing ultra-pure polyethylene with respect to the long term performance of cable insulation properties? Some attempts to use nano-filled polyethylene for HVDC applications had recently been reported. Are there any longer experiences with application of such materials?

4. Preferential Subject No 2 – Emerging Test Techniques and Diagnostic Tools

The submitted 17 papers of PS2 are divided into the following sections:

- insulation diagnostics in oil filled equipment (5 papers)
- diagnostics of water tree degradation in power cables (1 paper)
- test procedures for ultra high voltage (UHV) substation equipment (1 paper)
- evaluation of high-voltage impulse waveforms (2 papers)
- new aspects on partial discharge (PD) diagnostics and asset management (5 papers)
- atmospheric and altitude corrections, harsh conditions (3 papers)

4.1 Insulation diagnostics of oil filled equipment

4.1.1 Overview of submitted papers

Paper D1-204 shows that wettability of Kraft paper, defined by means of contact angle measurements with polar liquids (formamide and diiodomethane), correlates well with paper's degree of polymerization (DP). The authors therefore postulated that contact angle measurements are applicable for practical determinations of the degree of ageing in power transformer insulation.

Paper D1-205 reports a comparative study performed on a set of commercially available capacitive sensors for estimating moisture content in oil filled power equipment. The purpose of the work was to check the accuracy, repeatability and reproducibility of the various commercially offered products as well as to calibrate their indications against standard Karl Fisher titration analyses (IEC 60422). It is shown that a conversion of the relative water saturation (as per indications of capacitive sensors) to the absolute humidity content in ppm is possible, but a subject to determining solubility coefficients for each specific liquid. Such data can also be used for setting warning and limit values not only for mineral oils but also for other insulating fluids. Also *paper D1-215* provides a comparison of statistical data from in-service experience with moisture estimations by means of Karl Fisher titration and capacitive moisture sensors in a large population of oil-filled power transformers. Significant discrepancies between the moisture levels estimated by the both methods have been found.

Paper D1-207 presents a modernized apparatus for laboratory testing of insulating fluid decomposition under ultrasonic cavitation. As the cavitation process induces specific gaseous by-products of the degrading liquid, chromatographic analyses of the dissolved gases (DGA) were performed and interpreted according to the various known procedures (Doernenburg ratio, Rogers ratio, IEC 60599, Key gas method, Nomograph method and Duval's triangle). It is claimed that in approx. 50% of the analysed cases the decomposition by-products were not correctly identified, which calls according to the authors for a need to further develop DGA interpretation tools.

Paper D1-216 discusses the influence of paper type and geometric factors on the impulse (SI, LI) and AC breakdown strengths of laboratory models of turn-to-turn and section-to-section of transformer insulation. It is concluded that the type of paper and conductor end roundness have little impact on the breakdown voltage while a presence of micro-voids as well as length of the winding influences this parameter stronger.

4.1.2 Questions

Question 2.1 Contact angle measurements are known to be sensitive to material's surface roughness. Are there any indications that sensitivity of the measurements may be affected by this parameter, so a separate calibration would be necessary for each type of paper? As water is very hygroscopic, samples taken from transformers will quickly change water content: How will wettability depend on sampling procedures. What is the advantage of measuring wettability compared to measuring DP?

Question 2.2 On-line capacitive moisture sensors have been in use for some time and the necessity for calibrating their indications separately for various oils complicates interpretation of the results. How can variation of oil properties be managed during service; is there a need for periodic calibrations?

Question 2.3 Interpretation of the results of DGA have been in focus within CIGRE for many years. Is there an agreement that additional interpretation schemes may still be needed for including the effect of cavitation, as claimed by the author of paper D1-207?

Question 2.4 The empirical relation derived in paper D1-216 to describe the influence of winding length on the breakdown strength of laboratory winding models yields a reduction of this parameter by 15% for long windings (500 m and 1000 m) as compared with short test samples. Is there a general agreement concerning this estimation? Is there any correlation of this observation with the weakest link, volume and/or surface models?

4.2 Diagnostics of water tree degradation in power cables

4.2.1 Overview of the submitted paper

Paper D1-210 refers to an earlier method for diagnosing water tree initiated deterioration of insulation in distribution power cables developed in Japan. The method is called "residual charge method" and relies on depositing space charges in water trees of a degraded cable by pre-stressing it with a DC voltage and then allowing to relax for certain time in a grounded state. Thereafter an AC voltage is applied to release the residual (deeply trapped) space charges. Recent works on further development of this method has revealed that the use of charging and depolarizing voltage pulses (duration ~1 ms) instead of the DC/AC voltage combination, yields an improved sensitivity of the procedure, reduction of the measurement time and reduction of the equipment size. It also allows for performing tests on a broader range of extruded cable types, including dry-cured cables with extruded semiconducting layers as well as on cables connected to GIS. Moreover, a correlation between the residual charge signal and the AC breakdown voltage is reported.

4.2.2 Questions

Question 2.5 Is there an elaborated knowledge on how to select the warning criteria for cable maintenance (replacement or monitoring), based on the proposed procedure, and what are respective practical experiences of the users of the procedure?

4.3 Test procedures for ultra high voltage (UHV) substation equipment

4.3.1 Overview of the submitted paper

Paper D1-211 reports on high-voltage test techniques for UHV equipment. The authors describe a new reliability evaluation method for oil insulation based on experimental results and evaluate the PD acceptance criteria for UHV power transformers. Special issues for the combined voltage test (AC/impulse) are explained and documented by experiments.

4.3.2 Questions

Question 2.6 The high-voltage test techniques for UHV equipment are under discussion by CIGRE and IEC. What are the differences in test techniques for UHV equipment compared with HV/EHV equipment? Is there any influence expected on the reliability of UHV equipment due to the new test techniques?

4.4 Evaluation of high-voltage impulse waveforms

4.4.1 Overview of the submitted papers

Two papers discuss the evaluation of parameters of high-voltage impulse waveforms. *Paper D1-203* evaluates the differences in the results obtained by different analysis procedures described in the current IEC and IEEE standards based on recorded impulse waveforms and waveforms generated by the IEC Test Data Generator. Further improvements of the relevant standards are necessary for switching impulse evaluation. *Paper D1-206* discusses the application of the new k-factor filtering to impulse waveforms generated during impulse voltage testing of different power equipment. The paper shows that accurate estimation of time parameters by the current IEC standard is not applicable in general to all impulse waveforms.

4.4.2 Questions

Question 2.7 What are the appropriate measures to overcome the present challenges of impulse waveform parameter evaluation? Is there a need for individual k-factor functions regarding different insulation materials or voltage classes (UHV vs. HV/EHV)?

4.5 New aspects on PD diagnostics and asset management

4.5.1 Overview of the submitted papers

Papers D1-202 and *D1-217* deal with the application of the UHF method for PD detection and location in power transformers. Some case studies are presented by Paper D1-202 and the PD results using the UHF method are compared with results from conventional PD measurement (IEC 60270). The UHF signal is used for triggering acoustic sensors for PD location. *Paper D1-217* focuses on a new locating method for PD based on electromagnetic wave propagation and signal acquisition using multiple UHF sensors. The locating method is supported by FDTD computer simulation and is proven by application of a newly developed UHF PD monitoring system on a 154 kV transformer.

Paper D1-208 reports on the calibration constant and associated uncertainty of HFCT sensors for unconventional PD measurement on HV cables. The performed simulations with different sets of PD pulses and band pass characteristics of HFCT sensors show an uncertainty result of less than 10% using the proposed evaluation method for apparent charge.

Paper D1-209 focuses on the description of a wideband antenna sensor for PD measurement in the frequency range from 0.1 – 100 MHz in combination with a portable PD instrument. The position of the antenna sensor and the distance from the components under test influence the measurement results during field tests.

Paper D1-214 describes the importance of power failure investigations in effective asset management of utilities. The lessons learned from power failure root cause analysis provide important life cycle data which will improve the future asset quality and prevent future failure occurrence.

4.5.2 Questions

Question 2.8 The UHF method for PD detection is applied worldwide since more than 25 years and a lot of experience is available by capturing PD data. Is the UHF method already used for factory acceptance tests and site acceptance tests on power equipment?

Question 2.9 Is the performance of available unconventional PD sensors sufficient for sensitive PD measurements? What are the procedures for the PD detection, location and identification of defects with respect to risk assessment on AC equipment like power transformers or GIS? Are PD test procedures and PD pattern available for testing of DC equipment and what is the physical background for acceptance criteria?

Question 2.10 Which diagnostic data are available from failure investigations and condition monitoring and should be applied for asset management on power equipment (transformers, GIS, cables etc.)? What are the criteria for condition assessment and automatic generation of warning and alarm signals?

4.6 Atmospheric and altitude corrections, harsh conditions

4.6.1 Overview of the submitted papers

Paper D1-201 describes the atmospheric correction for positive lightning impulse voltages under high humidity conditions in respect to actual IEC and IEEE standards. Experiments are performed under natural air conditions with absolute humidity between 7 and 25 g/m^3.

Paper D1-212 focuses on the application of weather models for the evaluation of design ESDD for harsh pollution conditions. A modified wind model is proposed and verified by case studies at four different test sites. Results of the verification of ESDD modelling in different countries are presented.

Paper D1-213 presents state-of-the-art atmospheric and altitude correction for dielectric strength of external insulation in respect to recent investigations on altitudes of up to 5000 m. The results are of interest for the performance of air gaps and clean insulators as well as for insulators in polluted conditions.

4.6.2 Questions

Question 2.11 What is the physical background for different values of exponent m related to the length of air gaps, insulator profile, insulator material, altitude, and pollution severity at

AC and DC voltage? Is there a significant influence of pollution conditions on the development of AC and DC transmission systems for altitudes > 1000 m? Is there a need for further investigations on the atmospheric correction procedure to consider high humidity?

Question 2.12 The modelling of ESDD and its calibration using DDDG measurements are described. What are the benefits and limitations of the ESDD modelling? What is the influence of the type of pollution on the correlation of Pollution Index and ESDD?

5. Preferential Subject No 3 – Properties and Potential Applications of New Materials

5.1 Overview of submitted papers

Paper D1-301 discusses applicability of IEC 61788-3 standard for determining the critical current in 2nd generation (2G) high temperature superconducting (HTS) tapes. Positive conclusions are drawn based on the performed experiments. It is however pointed out that special precautions need to be taken regarding specimen mounting, soldering procedure as well as duration and level of the applied current and the measure voltage, especially for the tapes that are not stabilized with copper.

Paper D1-302 presents results of investigations on moisture migration between cellulose and ester in impregnated insulation systems composed of neutral and thermally stabilized Kraft paper immersed in natural ester oil. The tests included thermal ageing of the insulation models in laboratory and a 30 months long test with a real power transformer with inserted paper samples. Water content and neutralization number were periodically evaluated in the oil, whereas degree of polymerization (DP), mechanical properties and infrared spectra were analysed for the paper samples. In the latter case the analyses concentrated on estimating if paper esterification could take place during the ageing. The obtained results indicated a stronger reduction of DP value for the neutral Kraft paper as compared with the thermally stabilized one, though no evidences for paper esterification could be detected in both the cases.

Paper D1-303 reports on the effect of dispersion of semi-conductive TiO_2 nanoparticles in a heavily aged mineral oil on its dielectric breakdown strength. The oil ageing was performed at 130°C for 36 days until the neutralization number exceeded the operating limit (0.1 mgKOH/g). It is demonstrated that the particle addition significantly impedes the deterioration of the AC breakdown strength of the aged oil. At the same time, it also yields an increase of the impulse breakdown strength by 30-40% as well as a reduction of the streamer propagation speed. An attempt to explain the observed effects is presented by studying the behaviour of space charges in the oil associated with the modification. The use of pulse electro acoustic (PEA) and thermally stimulated depolarization (TSD) techniques has revealed a strong reduction of space charge decay rate.

Paper D1-304 compares the impacts of sandstorms, industrial pollutants (cement and fertilizers) and immersion in high concentration acid solutions on the decay of water repellent property of silicone rubber insulators. The wettability of the insulators was evaluated by means of contact angle measurements. It is shown, as also reported earlier, that all the stress factors have an impact on the insulator hydrophobic properties.

Papers D1-305, D1-306 and *D1-308* deal with aspects related to the required reduction of SF_6 usage in high voltage equipment. *Paper D1-305* summarizes the research conducted during recent years with various fluorinated molecules. It concludes that a few percent addition of fluoronitrile gas to CO_2 (GWP reduced by 98%) provides in this respect a great potential as compared to other considered gas mixtures, as it allows for maintaining a similar strength as pure SF_6 at presently used pressure level. The physical, switching and thermal performance of this gas mixture also appears satisfactory. In *paper D1-308* results of dielectric tests of a 30:70% mixture of trifluoroiodomethane (CF_3I) and CO_2 are presented. However the low arc quenching capability and high boiling point limit the potential area of CF_3I mixture use to GIL applications. In contrast to the previous two, *paper D1-306* concentrates on an attempt to find an optimal mixing ratio of gas constituents (N_2, O_2, CO_2, Ar) for the applications in gas insulated switchgear. Various binary concentrations of N_2 and O_2 were analysed based on macroscopically derived discharge parameters (swarm parameters), which indicate a possibility of reaching about 5% strength improvement by increasing the content of O_2 in the mixture.

Paper D1-307 discusses a possibility for replacing thermosetting resins, e.g. epoxies, by recyclable polymers in solid insulation elements of gas insulated switchgear. Polyethylene-terephtalate (PET) is presented as the candidate material for the replacement based on a rage of investigations of its mechanical, electrical and thermal characteristics as well as in service operated encapsulated equipment rated 72.5 kV.

Paper D1-309 presents results of intensive research activities on development of fabrication of functionally graded materials (FGM) with various profiles of permittivity (ε) distribution for use as spacers in GIS. The ε-FGM effect has been achieved by means of centrifugal force in post-type and coaxial disc-type solid insulators by mixing various metal oxide filler particles of different size in epoxy resin base. Applications of such insulators will allow for a better control of electric field distribution along the spacers and therefore for enhancing the breakdown voltage and the ageing stability of power apparatuses. The authors also present a concept of electric field control along GIS spacers by depositing on their surfaces thin semiconducting layers (σ-FGM) of well controlled conductivity and length.

5.2 Questions for Preferential Subject No 3

Question 3.1 An extensive development of 1G BSCCO and 2G YBCO HTS types have recently been witnessed, each of them having own advantages and disadvantages. What are the most recent achievements as regards 1G and 2G HTS, in terms of critical current I_c level and its determination, n-values, ac loss, mechanical stabilization, uniformity, etc. What about manufacturing speed and accessible length from the viewpoints of HTS applicability in actual power apparatuses?

Question 3.2 Transformers insulated with paper impregnated by natural or synthetic esters become more and more popular in power networks. What are experiences of other users with regard to the insulation reliability and ageing performance as compared with the traditional mineral oil impregnated insulation?

Question 3.3 A possibility of impeding or even improving resistance of insulating liquids to electrical degradation by addition of nano-filler particles provides an attractive option. Are there examples of in-service operating transformer insulated with nano-filled fluids and what are the related experiences?

Question 3.4 The impact of various natural contaminants on the properties of water repellent silicone rubber insulators has been reported broadly in literature. However, questions are still being raised concerning the representativeness of the acid immersion tests. Are there any proved evidences that the immersion tests can really mimic the naturally appearing environmental service conditions?

Question 3.5 Two alternative solutions have been considered when attempting to reduce the use of SF_6 in gas insulated high voltage equipment. One of them relies in introducing gas mixtures with a reduced content of various fluorinated compounds while the second one concentrates entirely on the components of air. Are there other examples of practical solutions of GIS and GIL that may indicate which of the alternative technologies will become dominating?

Question 3.6 One of the deterioration mechanisms of solid GIS insulator surfaces reported in literature is associated with electrical tracking. Is there a need for testing the resistance to tracking and erosion on materials for such insulators?

Question 3.7 It is postulated that introduction of ε-FGM or σ-FGM spacers in GIS installation can contribute to simplification of their construction (compactness), lower cost and energy saving. Are there any specific examples where such solutions have already been applied and what is their impact of the above mentioned factors?